TITLE: DETERMINING THE DYNAMIC PROPERTIES OF DEVONIAN GAS SHALE

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ABSTRACT

Four techniques are used to characterize the response of Eastern Devonian gas shales to impulsive loading. First, the elastic moduli of the transverse, isotropic shales are measured. Then, tensile strengths are deduced from an examination of sampl'' recovered from impacts with characterized plates. Third, shock velocities, release wave velocities and stress-strain paths are determined from measured stress wave histories at various depths in the shales. Finally, the pressure-volume relation for these shales are determined from shock velocity measurement to pressures as high as 80 GPa (800 kbars) using impacts from high-explosive driven metal plates.

INTRODUCTION

Successful prediction and optimization of explosive effects in geologic materials requires knowledge of the constitutive relations governing the rock response to impulsive loading. Such constitutive relations must include descriptions of both wave propagation and fracture phenomena under dynamic stress. The initial phase of our program therefore was directed toward acquiring these basic data. Here, some of the dynamic properties of gas shales and the techniques used to determine them are discussed.

ELASTIC PROPERTIES

The determination of the elastic constants of gas shales is the first step towards understanding the shale's response to both static and dynamic stresses. The samples whose dynamic properties are presented here were cut from two pieces of 4-inch-core from the Columbia Gas Company Well No. 204U2, one from approximately 1040 m and the other from 1039 m below the surface. X-ray diffraction patterns showed both to be common illite shales where the composition is very fine silica or quartz grains and a minor amount of anhydrous clay minerals. The densities of the two pieces are 2.7 Mg/m³ (1040 m in depth) and 2.4 Mg/m' (1039 m). These densities span a commonly accepted bulk density of 2.55 Mg/m³ for Eastern gas shales.

The symmetry of the elastic properties of Eastern gas shales is transverse isotropic. This means that there is an elastic symmetry axis of rotation perpendicular to the bedding and an elastic axis of two-fold symmetry in the bedding planes. The samples were prepared for sound speed measurements by cutting them into plates 30 to 60 mm in diameter and 2.0 to 7.5 mm thick at angles 0°, 45°, and 90° to the bedding. Densities were determined using the immersion method. The sound speeds were determined from the difference in the time an ultrasonic pulse took to traverse an aluminum plate and the combination of the same aluminum plate and a gas shale plate. Because of interferences of the ultrasonic pulses at the shale bedding interfaces, only first pulse arrivals were measured.

We have assumed that the elastic wave velocities are a linear function of density over the density range studied here. The linear equations for the five different propagation modes measured are listed below with a description of each.

$$V_1(km/s) = +1.679 + 1.277 \rho$$
$$\rho = 2.4 \text{ to } 2.7 \text{ Mg/m}^3$$

V_1 is the longitudinal velocity directed parallel to the shale bedding.

$$V_3(km/s) = +1.003 + 1.805 \rho$$
$$\rho = 2.4 \text{ to } 2.7 \text{ Mg/m}^3$$

V_3 is the longitudinal velocity directed perpendicular to the shale bedding.

$$V_4(km/s) = -1.332 + 1.438 \rho$$
$$\rho = 2.4 \text{ to } 2.7 \text{ Mg/m}^3$$

V_4 is both the shear velocity directed perpendicular to the bedding of the shale, and the shear velocity directed parallel to the bedding with particle motion perpendicular to the bedding.

$$V_5(km/s) = +1.151 + 1.245 \rho$$
$$\rho = 2.4 \text{ to } 2.7 \text{ Mg/m}^3$$

V_5 is a quasi-longitudinal velocity directed at 45° to the bedding.

$$V_6(km/s) = +1.416 + 0.627 \rho$$
$$\rho = 2.4 \text{ to } 2.7 \text{ Mg/m}^3$$

V_6 is the shear velocity directed parallel to the bedding with the particle motion also parallel to the bed-

ding.

These velocities are then converted to the elastic moduli of a transverse isotropic solid. These are listed in Table I for the two density shales studied here and the average bulk density shale, 2.55 Mg/m³.

DYNAMIC TENSILE STRENGTHS

In a shock wave's divergent propagation from both spherical and cylindrical symmetries, the initial positive compression rapidly converts into tension, particularly the tangential component. This dynamic tensile stress is a major contributor to the fracture of the surrounding rock. Another form of fracture, though minor, caused by dynamic tensile stress is spalling. Spalling occurs behind a free surface at which a finite shock wave releases; the resulting rarefaction wave from the free surface and rarefaction wave following the shock collide and form a spreading tension wave. Thus, the dynamic tensile strength of rock is an important property to be determined when attempting to predict the fracture pattern of a rock. Here a technique is described for determining the dynamic tensile strength of gas shales; the results of studies using this technique are presented.

The technique involves impacting shales of known shock impedance and orientation to bedding with a thin driver of known shock impedance generating a well-defined shock in the shale. The impedance of the impactor plate is chosen so that the interface between the impactor and the sample separate after passage of the rarefaction wave from the rear free surface of the impactor. The rarefaction from the impact surface of the shales and their other surface which is free collide in the middle region of the shale samples creating a tension wave. The target plate in which the shale samples are mounted is recovered and the shales are removed and examined for spall. The experimental configuration is shown in Fig. 1.

Figure 1 shows a front view of a target plate (a) and a cross-sectional view of an impact experiment (b). The view, (a), shows the arrangement of the shale samples, D, of different densities and orientations are mounted in the target plate, B. Each sample is backed with low density (0.015 Mg/m³) plastic foam, H, to facilitate mounting the specimens' impact surfaces flush with the target plate's surface. The specimens are held in the plate with a thin layer of epoxy. Shorting pins, C, of various lengths are used to determine the velocity of the impact plate, G. The front surface of the impact plate is covered with a 0.01-mm-thick Al foil shorted to the projectile, E. A pulse is generated on a repetitive time-marked oscilloscope sweep as each charged pin is shorted. The muzzle of the 3-m-long, high-pressure gas gun used to drive the projectile is labeled A, the target plate mounting screws are labeled I, and the unsupported area behind the impact plate is labeled F.

The impedance of a material at low stresses is the longitudinal sound speed in the direction of propagation times the material's density. The tension generated in these shales is the product of the impedance of the impact plate and the shale samples' times the impact plate's velocity divided by the sum of the two impedances. The impact plate material used here was PMMA. We found that shales having a density of 2.69 Mg/m³ would not spall under tension as high as 66 MPa (0.66 kbars) if the tension waves propagated

along the bedding, but shales of a similar density, 2.57 Mg/m³, spalled as low as 45 MPa (0.45 kbars) if the tension waves propagated perpendicular to the bedding. For shales having a density of 2.40 Mg/m³, the tensile strengths were less than 40 MPa for both propagation directions. The stress rates involved in these experiments are of the order of 1 GPa/μs (10 kbars/μs) and regions under tension remain in tension only about 2μs if they do not spall. Experiments involving lower stress rates and longer tension durations would find the tensile strengths of the gas shales to be smaller.

RESPONSE TO PLANE STRESS IMPULSES

Properties of gas shales in response to dynamic stress can best be determined from the analysis of the degradation of stress impulses as they pass through the shales. The technique used here is to measure the stress history of an impulse at several depths in a shale sample. The sample assembly consists of a stack of shale plates all 40 mm in diameter. The first plate is 2 mm thick, the second and third plates are 4.5 mm thick; and the fourth is 5 mm thick. The impactor plate is usually 3 mm thick. The density, elastic properties, and orientation of all plates are matched. Between the shale plates of the sample assembly are 50-ohm grids of 0.01-mm-thick manganin foil that cover an area of 40 mm² in the center region of the plates. The resistance of the grids are well defined as a function of stress under impact conditions. The resistance is deduced from the voltage generated at the null point of a pulsed Wheatstone bridge caused by the change in resistance of the manganin grid. The sample-manganin gage stack is placed in a target plate and surrounded by velocity pins; see Fig. 2.

Eight experiments were conducted. The differences between them were the orientation of the bedding to the direction of planar shock propagation, the shale densities, and the stress levels. The response of the shales to the shock loading and unloading was calculated using a computer code, GUINSY2, written by Lynn Seaman of Stanford Research Institute. The theory on which the code is based and an explanation of how the code is used was described earlier by Seaman.[1] The analysis requires the stress histories, a correlation of regions on the stress profiles, the initial density of the shales, and the initial gage locations. From the analysis the specific volume, the particle velocity, and internal energy of the shales are correlated with the stress as a function of time at each gage location.

The results of one experiment shown here, Figs. 3 - 5, are for a 2.44 Mg/m³ shale with the stress wave propagating perpendicular to the bedding (90° orientation). The longitudinal velocity in that direction is 3.3 km/s. Figure 3 shows three stress histories deduced from the resistances of 3 manganin gages located at three different depths in the shale (upper right hand corner of Fig. 3). All three histories have a common time base in relation to each other. The stress-strain path calculated from these histories is shown in Fig. 4. The loading path shows a gradual curvature indicative of gradual elastic to plastic yielding. The hysteresis between loading and unloading is very small showing strong elastic response at this particular stress level, 0.5 GPa (5 kbars). The plot of wave velocity as a function of particle velocity (proportional to stress) clearly shows a fast moving elastic toe, ~ 3.45 km/s, which yields to a slower stress wave front which gradually slows with increasing stress (~ 3.2 km/s). The initial release wave velocity travels at ~ 3.8 km/s.

HUGONIOTS OF EASTERN GAS SHALES

The response of the gas shales to large shocks, between 10 and 100 GPa, was determined from simultaneous measurements of the shock wave velocities through gas shale samples and through a standard material whose Hugoniot equation of state under shock compression is well known. The experimental technique is described in detail elsewhere.[2] From the measured shock velocities through both the shales and the standard, the mass or particle velocities through the shales are deduced.

The shock state of gas shale is completely defined by knowing only the shale's initial density (ρ_o), the shock velocity (U_s), and the particle velocity (U_p). The pressure (P) and compression (1-V/V) for the shale are derived from the above three parameters using the following relations

$$P = \rho_o U_s U_p, \quad V/V_o = (U_s - U_p)/U_s.$$

The locus of U_s, U_p data for material not undergoing transitions in structure or bonding is usually linear

$$U_s = c + s U_p.$$

Hugoniot data was collected for the two different density shales with shock waves, propagating both perpendicular to and along the bedding. Data for 2.41 Mg/m^3 shale with the shock-wave propagating perpendicular to the bedding are shown in Fig. 6. The data can be fit satisfactorily with two linear fits with a break between them at approximately $U_s = 5.75$ km/s. This indicates that there is a discrete reduction in the volume of the shale at the pressure associated with that shock pressure, 20 GPa. The volume reduction at that pressure between the two Hugoniots is 6% for the 2.4 Mg/m^3 shales and 7% for the higher density shales. Since the major component of the gas shales is quartz (30% to 60% by volume) the change in volume can probably be attributed to the α-quartz to stishovite phase transformation. The transition pressure found here is 6 to 10 GPa above the quartz-stishovite pressure where the transmission occurs at 25°C (extrapolated from high temperature, static high pressure data) and occurs under shock compression. respectively. There are several explanations for this difference. The first is that the quartz, floating in a matrix of kerogen and other materials, requires time to "ring up" in pressure and to transform, resulting in a shock wave, whose velocity is measured, being followed by a relaxation wave caused by that transition. Below 20 GPa the shock wave is not overrun by the relaxation wave for the sample thickness used here, 5 mm. The other explanation is that because of shock heating caused by pore collapse and compression of the kerogen, the normal equilibrium transition pressure for quartz is shifted to higher pressures. The knowledge of which explanation is correct may be important since the first explanation would mean that the shales may be able to absorb large amounts of energy at pressures as low as 10 to 14 GPa.

REFERENCES

1. Seaman, L., Lagrangian Analysis for Multiple Stress or Velocity Gages in Attenuating Waves, J. Appl. Phys. 45, 4303-4314, 1974.

2. McQueen, R. C., Marsh, S. P., and Fritz, J. N., Hugoniot Equation of State of Twelve Rocks, J. Geophys. Res. 72, 4999-5036, 1967.

Table I. Elastic Moduli of Eastern Gas Shales

Density (Mg/m^3)	:	2.40	2.55	2.70
C_{11} (GPa)	:	54	62	71
C_{33} (GPa)	:	26	33	41
C_{44} (GPa)	:	11	14	18
C_{66} (GPa)	:	20	23	26
C_{12} (GPa)	:	13	16	19
C_{13} (GPa)	:	17	17	16
Bulk Modulus (GPa)	:	23	26	29

50 mm

(a)

(b)

I

H
G
F
E
D

C

B

A

IMPACT PLATE

AL PROJECTILE

AL SAMPLE
HOLDING PLATE

SAMPLE
GAGE STACK

VELOCITY
SHORTING PIN